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SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

V

PLUME FAR FIELD FLOW AND RADIATION CALCULATIONS

Final Report

by

F. W. Vogenitz

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Huntsville, Ala. 35807

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1. SUMMARY

A time-dependent Monte Carlo computer code which simulates the far-field interaction between a rocket exhaust plume and an ambient flowing gas was developed. Computer calculations were carried out for a rocket motor firing in both continuous and pulsed modes. The pulsed mode calculations employed the Baum, Kolb, Rieger, and Sutton Radiation Model[1] for the atomic physics of the H_2O molecule, which provides estimates of radiant flux from the interaction region. From the pulsed mode calculations, it was found that, for the assumed rocket motor properties and operating characteristics of 600 pounds thrust and .007 seconds burn time:

1. At altitudes above 200 km, for times less than 3 exhaust molecule mean free times, and for angles between relative wind and sensor look axis of 90° or less:

    a) the flow is in the "free streaming shell regime"

    b) the order of magnitude of the power on a detector can be estimated by a simple calculation -- the dominant contribution comes directly from the free molecular interaction between the shell of exhaust gas and the ambient gas

    c) the power on a detector can be scaled simply with magnitude and orientation of the relative wind by taking the vector sum of U_∞ and $U_{exhaust}$.

2. The time for the disturbance to be blown away is sensitive to the orientation of the relative wind.

(1) H. Baum, C. Kolb, T. Rieger, E. Sutton, A. Germeles; "(S) Water Vapor Rotational Band Radiation From High Altitude Rocket Plumes (U)" Aerodyne Research, Inc. Report No. RN-6, March 1972.

2. INTRODUCTION AND BACKGROUND

At high altitudes in the mixing zone between the highly expanded portion of a rocket exhaust plume (the plume "far field") and an ambient supersonic stream, the flow is strongly influenced by non-equilibrium molecular transport processes. Chemical reactions occurring in the flow may not be describable by thermal rate coefficients and proper description of radiation from the mixing zone may require an accurate determination of the molecular velocity distribution.

A method which has been demonstrated to be very successful in describing such flows is the Monte Carlo Simulation Technique, in which the molecular motion is simulated on a digital computer using the Monte Carlo random sampling method. The technique is well suited to treat geometrically complex, time dependent, three-dimensional flows. Recent extensions to the technique enable chemical reactions and radiation to be described in the simulation.

A Monte Carlo code has been developed to describe the radiation due to the time-dependent, three-dimensional interaction in the far field between an ambient flowing gas and a cloud of exhaust gas molecules emitted by a rocket firing pulse of specified duration. The computer code capabilities include the following:

a) The angle between the rocket exhaust axis and the relative wind is an input variable, to enable the effect of orientation to be identified.

b) As initial condition for the interaction calculation, the cloud of exhaust gas molecules is assumed to be "inertia dominated" and hence is prescribed to form a source-like collisionless flow which can be well approximated using inviscid method-of-characteristics theory.

c) A "general radiation model" is incorporated in the code. The reactive collision cross sections to create and destroy radiatively-active species are assumed as input data,as a function of impact

parameter and relative kinetic energy. The mean radiative lifetime is assumed. Using this information, during the calculation of the flowfield, collisional excitation of molecules is allowed to occur with the appropriate probability. For each newly excited molecule, a radiative lifetime is sampled from the appropriate distribution. Each excited molecule is tracked in the flow, checking each subsequent collision for the possibility of deactivation, until the time to radiate is reached. The resulting photon flux, as a function of location in space, is recorded during the calculation.

d) As an alternative to the radiation model described in c) above, the "effective radiation rate constant" from the Baum, Kolb, Reiger, and Sutton Radiation Model[1] for H_2O was also incorporated into the computer program. This "rate constant" is essentially the average energy released per collision and is given as a function of relative velocity. Counters for each small region of physical space were set up in the code and were incremented at each collision by the appropriate amount. The emitted power from each region is then found by differentiating the cumulative energy curve.

3. DISCUSSION OF RESULTS

3.1 General

The time-dependent Monte Carlo computer code to simulate far-field plume interaction was completed at TRW in October 1971. Preliminary calculations to verify the code were carried out in October at the Safeguard computing facility in Huntsville, Alabama. Subsequently, a set of production calculations was carried out at Huntsville. The conditions for the calculations are shown in Figure 1.

Typical rocket motor characteristics were taken to be 600 pounds thrust and 7 milli-seconds burn time. The vacuum expansion flowfield used for initial conditions at the inner boundary of the field of view was generated by AVCO Everett Research Laboratory using the method of F. P. Boynton.

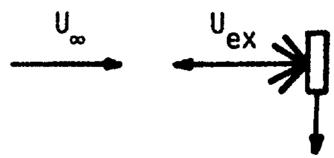
3.2 Preliminary Steady Flow Calculations

Two steady flow calculations, at simulated altitudes of 140 km and 200 km, were carried out. These were intended to investigate possible differences between the far-field interaction due to a rocket motor firing in a continuous mode and one firing in a pulsed mode.

Stagnation line profiles of the relative fraction of exhaust molecules and ambient molecules at 200 km are shown in Figure 2. The parameters characteristic of our assumed maneuvering rocket motor were used for this calculation, except that the burn time was made infinite, and the relative wind was aligned anti-parallel to the thrust axis; that is, the rocket motor is in retro-fire. The fractions of exhaust molecules and ambient molecules which have been scattered from the undisturbed exhaust or ambient state either by collisions with other scattered molecules or exhaust-ambient collisions are also shown in Figure 2. It can be seen that the shock layer is well "merged"; that is, external and internal shock waves are not apparent as distinct regions.

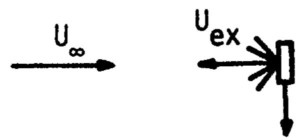
MONTE CARLO CALCULATIONS CARRIED OUT

(1) Preliminary Steady Flow Calculations

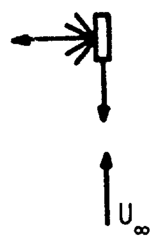


2D $\left\{ \begin{array}{l} \text{(a) 140 km} \\ \text{(b) 200 km} \end{array} \right\}$ 90° Angle of Attack

(2) Unsteady Flow Calculations



2D (a) 200 km
5 mean free times
90° Angle of Attack



3D (b) 200 km
3 mean free times
0° Angle of Attack

FIGURE 1

200 km Steady Flow - Retro Fire

Relative Density Profiles on Stagnation Line

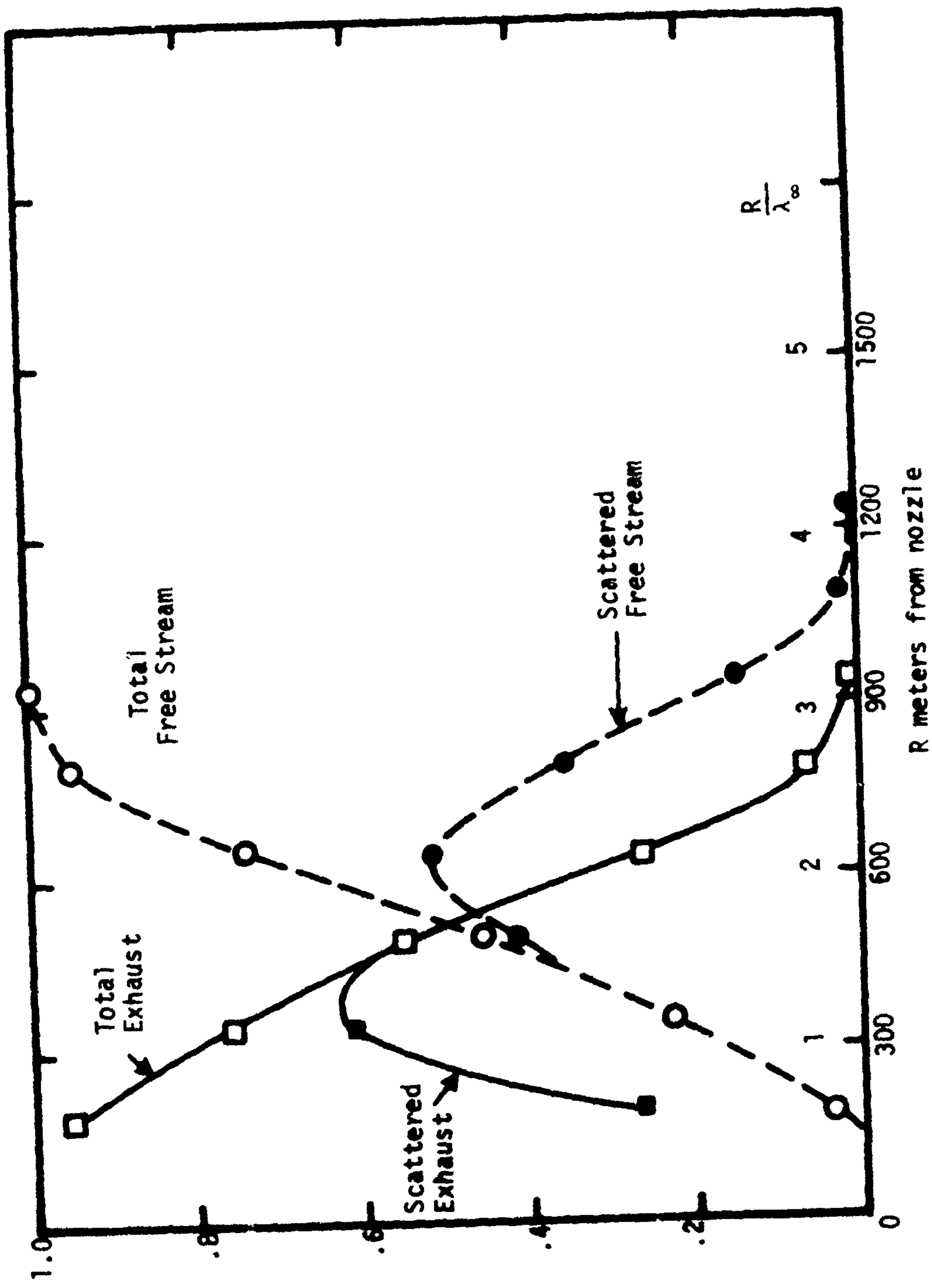


FIGURE 2

Comparison of these steady flow results and the unsteady flow results to be discussed below revealed substantial quantitative differences. Steady flow results thus would not be useful to make predictions for a motor firing in the pulsed mode.

3.3 Unsteady Flow Calculations

A tabulation of some characteristic flow interaction parameters for the assumed rocket motor firing intermittently is shown in Figure 3. Values of the ratio of shell width to exhaust molecule mean free path, $\Delta\ell/\lambda_{ef}$, are shown there. It seems likely that for altitudes of 200 km and above, where $\Delta\ell/\lambda_{ef}$ is $<< 1$, the shell of gas emitted by the rocket is too thin for there to be any significant "cascading" of collisions within the shell of exhaust gas. One would then expect the gas density in the shell to simply attenuate with distance from the nozzle due to geometry and due to collisions with ambient molecules. For altitudes between 140 km and 200 km a conclusion based upon such a simple analysis must be more tentative; however, it seems likely that somewhere between 140 km and 200 km the effect of "cascading" will become appreciable. It is not possible to make a similar a priori estimate for the interaction with the atmosphere of the molecules scattered from the shell.

3.3.1 Unsteady Calculation at 90° Angle of Attack

An unsteady calculation at 200 km altitude with the relative wind aligned anti-parallel to the thrust axis (90° angle of attack) was carried out using the "general radiation model" described in 2c). In Figure 4, the relative composition of the gas along the thrust axis is shown at 60 milliseconds, or one mean free time, after the start of the calculation. Five species are identified, including exhaust molecules which have been excited to an IR active state. The gas behind the shell is seen to be composed of approximately 70 percent undisturbed free stream molecules and 25 percent scattered free stream and exhaust molecules. Excited molecules form about 5 percent of the total. It should be pointed out that the "general radiation model" used in the code is an extremely simple one, utilizing a single step excitation. A more realistic radiation model was supplied by ARI[1] and used in a subsequent calculation, to be discussed in 3.3.2.

CHARACTERISTIC PARAMETERS

Shell width $\Delta \ell$ = .007 secs x 3,000 m/s $\approx$ 21m

Exhaust molecule m.f.p. $\lambda_{e-f} = \frac{U_{ex}}{An_\infty(U_\infty + U_{ex})} \approx \lambda_\infty/2$

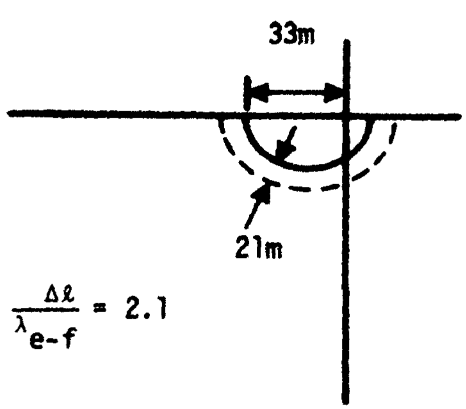
Mean free time for exhaust molecules $t_{e-f} \approx t_\infty/8$

λ_∞ = free stream mean free path

t_∞ = free stream mean free time

140 km

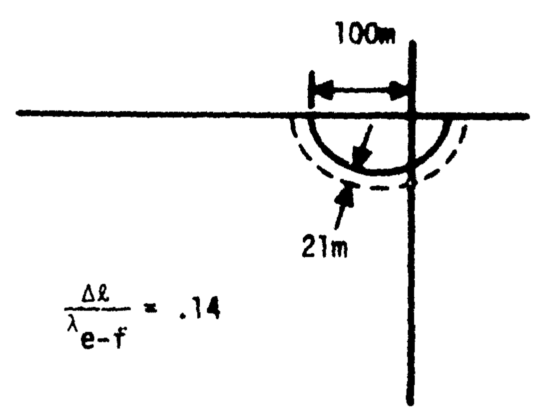
λ_∞ = 20m
λ_{e-f} = 10m
t_{e-f} = .004 secs



$\frac{\Delta \ell}{\lambda_{e-f}} = 2.1$

200 km

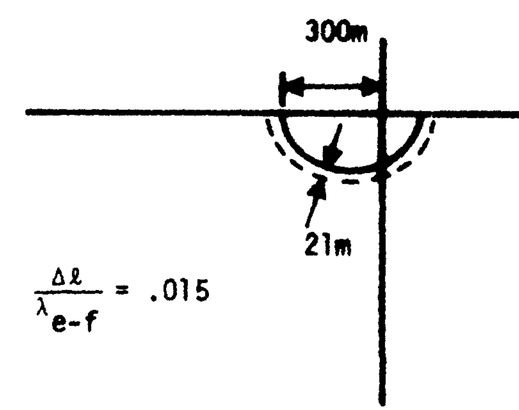
λ_∞ = 300m, t_∞ = .5 secs
λ_{e-f} = 150m
t_{e-f} = .060 secs



$\frac{\Delta \ell}{\lambda_{e-f}} = .14$

300 km

λ_∞ = 3800m
λ_{e-f} = 1400m
t_{e-f} = 1.0 secs



$\frac{\Delta \ell}{\lambda_{e-f}} = .015$

FIGURE 3

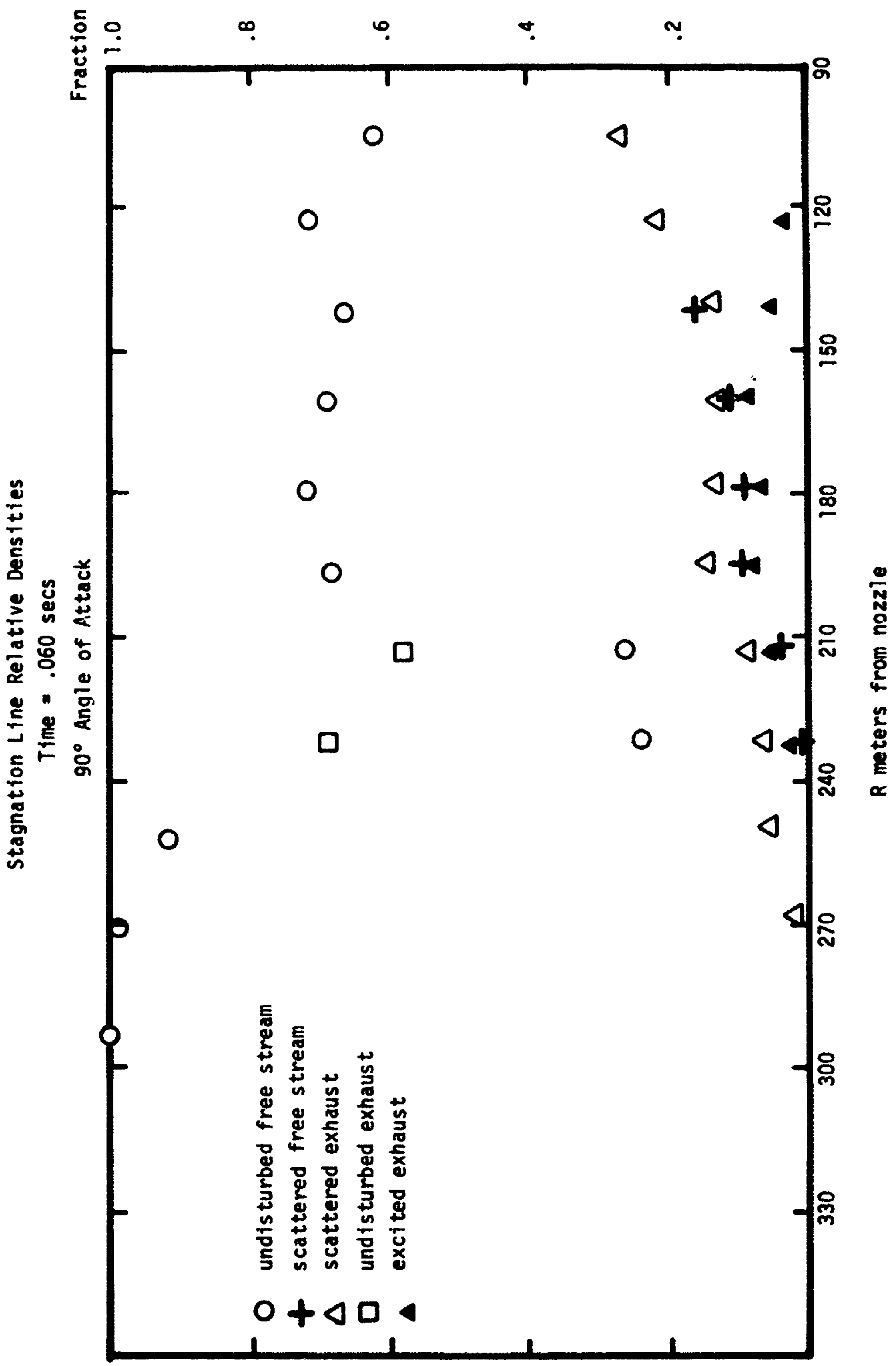

Stagnation Line Relative Densities
Time = .060 secs
90° Angle of Attack
Fraction
1.0
.8
.6
.4
.2
90
120
150
180
210
240
270
300
330
R meters from nozzle
undisturbed free stream
scattered free stream
scattered exhaust
undisturbed exhaust
excited exhaust

FIGURE 4

Figure 5 shows the cumulative radiative flux in two locations in the flow field, along the thrust axis and look axis, at 60 ms and 110 ms after the start of the calculation. The ordinate on the figure is the number of photons produced per local free stream molecule. Due to the simplicity of the radiation model and uncertainty in the magnitude of the excitation cross section, it is not known how much quantitative significance can be attached to the radiation information presented in Figure 5. Probably the most significant feature is that the ordinate value never exceeds one. Since the excitation cross section used in the calculation was equal to gas kinetic (reduced by a geometric factor), this means that each free stream molecule excites at most one exhaust molecule. Hence, it is clear that there is no "cascading" occurring in the shell of gas; molecules are simply knocked out of the shell to form a trail of scattered species behind the shell.

3.3.2 Unsteady Calculation at 0° Angle of Attack

An unsteady calculation at 200 km altitude with the relative wind aligned anti-parallel to the sensor look axis (0° angle of attack) was also carried out. The flow field for this case was found to be similar to that found at 90° angle of attack, that is, the shell of emitted exhaust gas is simply attenuated due to geometry and due to a free molecular interaction with the atmosphere, leaving a trail of scattered molecules behind it.

This calculation was terminated at 3 exhaust molecule mean free times (≈180 ms) after the leading edge of the shell crossed the inner boundary of the physical field of view. (The exhaust molecule mean free time = $\sqrt{2}\lambda_\infty/(v_\infty + v_{ex})$). This crossing would occur approximately 30 ms after ignition. The calculation at 90° angle of attack described in 3.3.1 was carried out to 5 mean free times. In both cases, scattered exhaust molecules were found to exist in significant quantity along the sensor look axis at the end of the calculation, to a greater extent at 90° angle of attack than at 0°. Thus the time for the entire disturbance to be completely blown away by the ambient wind is certainly greater than 3 mean free times for all relative wind orientations and will vary with the orientation angle. One can

Cumulative Radiation

90° Angle of Attack

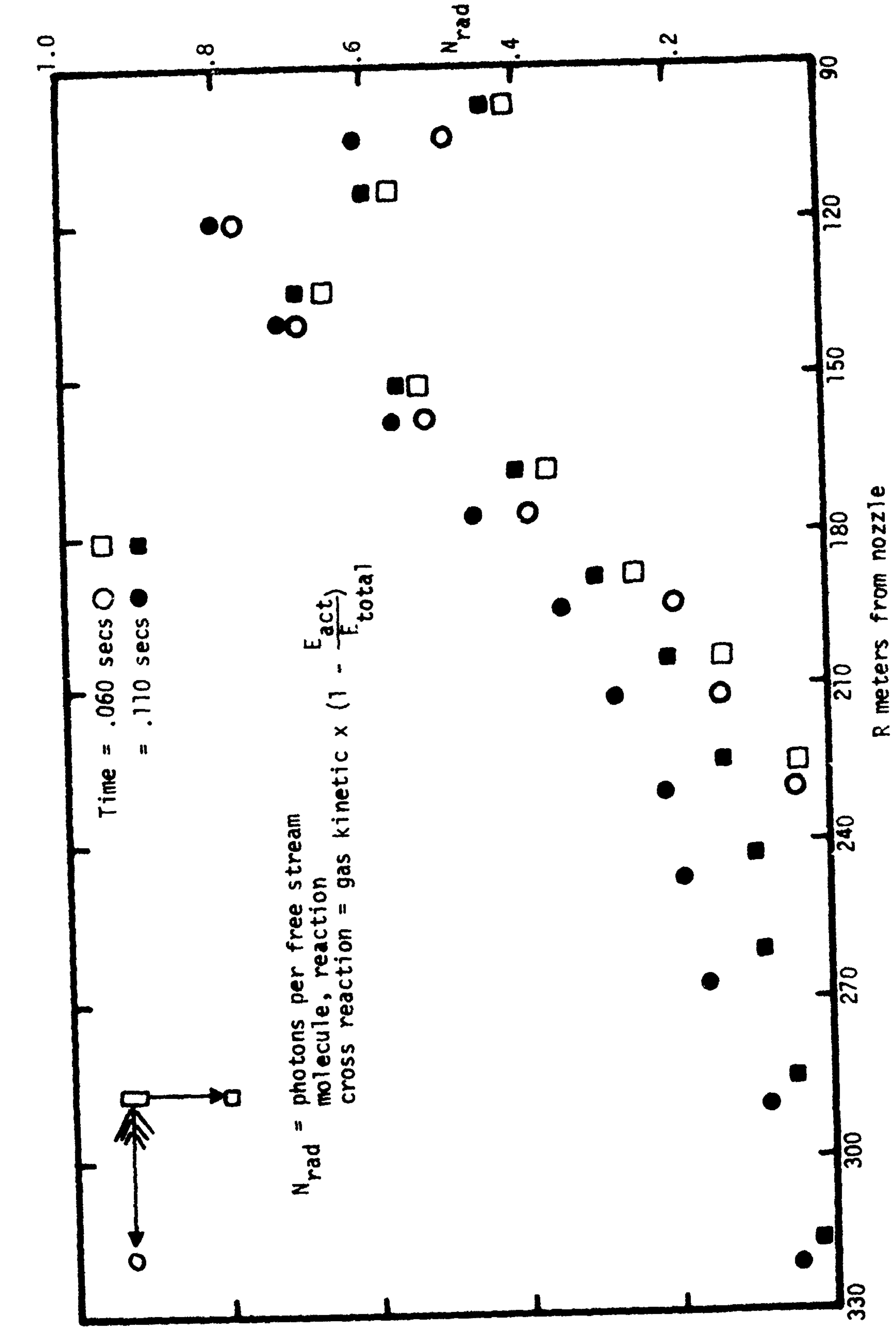


FIGURE 5

conservatively say that for times less than 3 mean free times, the flow is in the "free streaming shell" regime, as shown in Figure 6.

To obtain a realistic estimate of the radiance from the plume and the power on the detector the calculation described above also included the radiation model for H_2O from Reference 1. A curve of the variation with energy of encounter of the average energy emitted per collision for this model is shown in Figure 7. This information was supplied to TRW by ARI. An analytic fit to the ARI curve was incorporated in the Monte Carlo computer program, and at each collision a counter was incremented by the energy released appropriate to the relative velocity for the collision, as determined from the ARI curve. The physical space surrounding the rocket was divided into small incremental volumes (called cells) each with its own emitted-energy counter. Typical time histories of the cumulative emitted energy are shown in Figure 8 for two incremental volumes located at r = 35 meters and r = 45 meters, where r is the distance from the rocket motor along the sensor look axis. To obtain the emitted power from each volume the derivative is taken. The rapid initial rise for the two histories in Figure 8 is due to the passage of the shell of unattenuated exhaust gas. The contributions to the cumulative emitted energy are extremely small thereafter. Thus, the dominant contribution to the radiant power emitted per unit volume is clearly due to the free streaming shell interaction. The total power on the sensor is obtained by the linear integration with distance of the power per unit volume along the sensor look axis. For time less than 3 mean times, the contribution of the "hot" gas behind the shell, which is comprised of the molecules scattered from the shell, was found to be negligible. The Monte Carlo calculation of power on the sensor is shown in Figure 9 and is seen to be in close agreement with a free molecular hand calculation, using the Baum, etal model. The exhaust gas density for this hand calculation was taken to be the vacuum expansion density reduced exponentially with distance to account for collisions.

Because of the free molecular nature of the interaction, it is possible to scale the results in Figure 9 to other altitudes and flight velocities. Normalizing power by the cube of the ambient density, normalizing time by

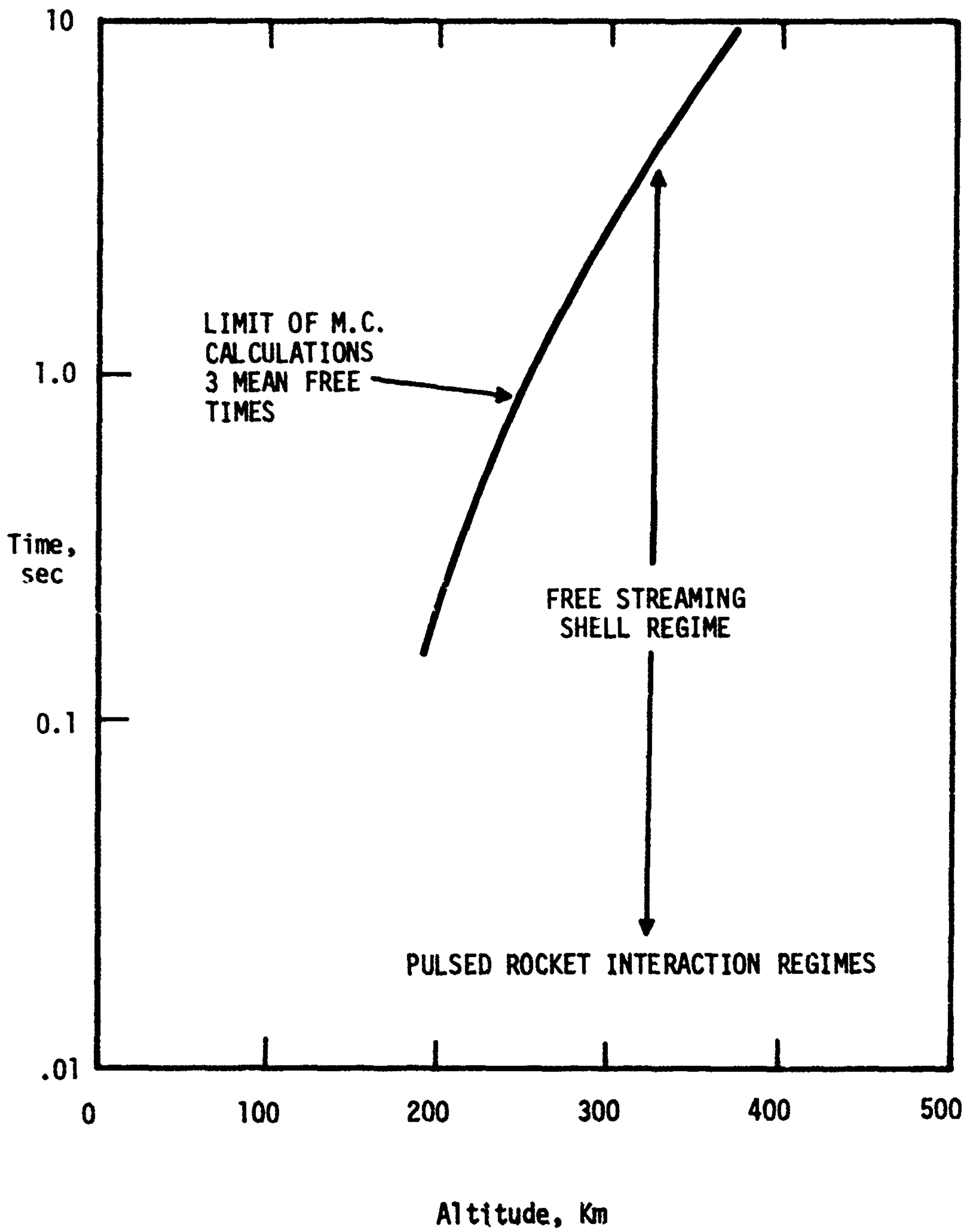

10
1.0
0.1
.01
Time, sec
LIMIT OF M.C. CALCULATIONS 3 MEAN FREE TIMES
FREE STREAMING SHELL REGIME
PULSED ROCKET INTERACTION REGIMES
0
100
200
300
400
500
Altitude, Km

FIGURE 6

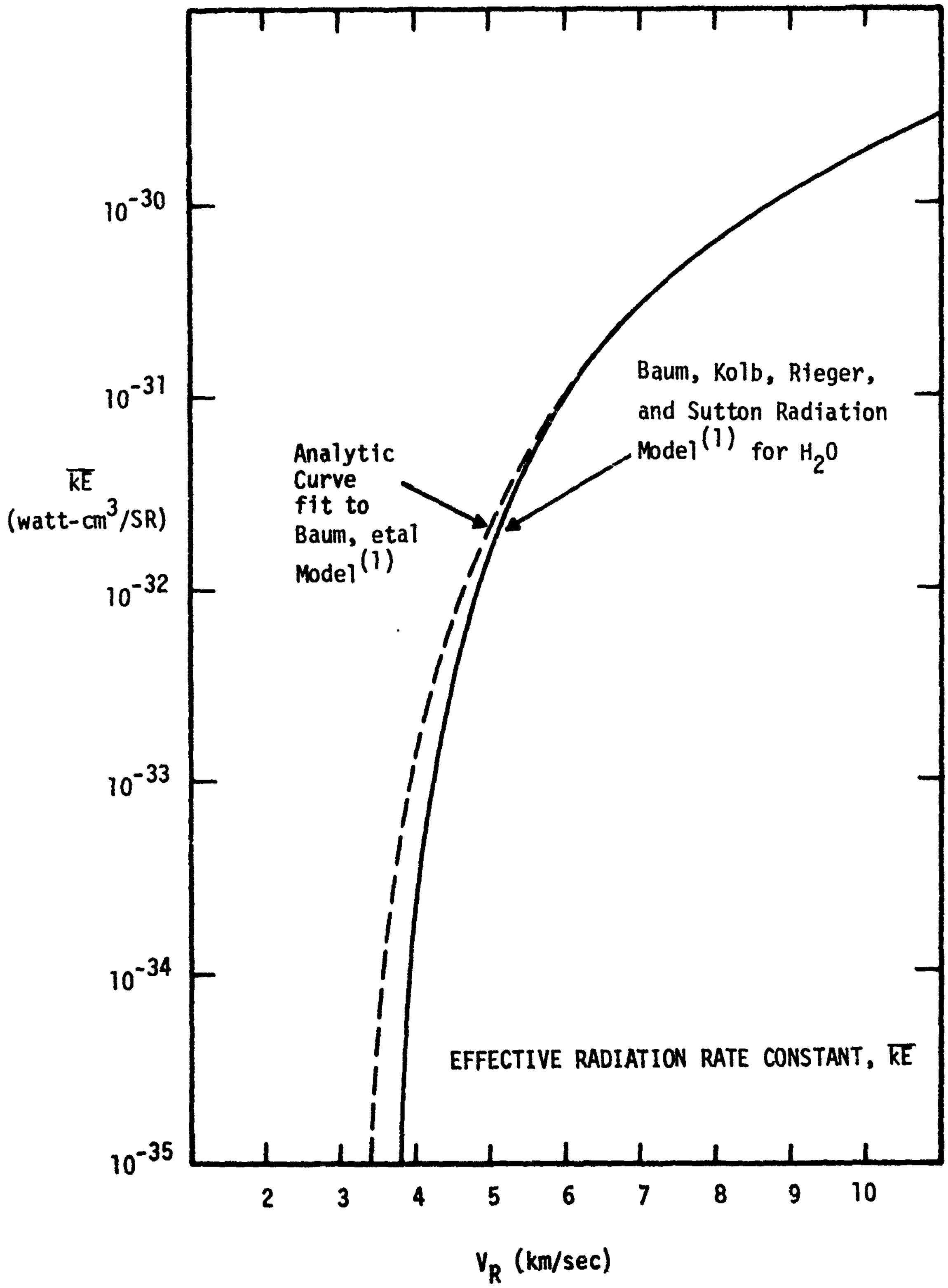

10^-30
10^-31
10^-32
10^-33
10^-34
10^-35
kE
(watt-cm^3/SR)
Analytic
Curve
fit to
Baum, etal
Model(1)
Baum, Kolb, Rieger,
and Sutton Radiation
Model(1) for H2O
EFFECTIVE RADIATION RATE CONSTANT, kE
2
3
4
5
6
7
8
9
10
VR (km/sec)

FIGURE 7

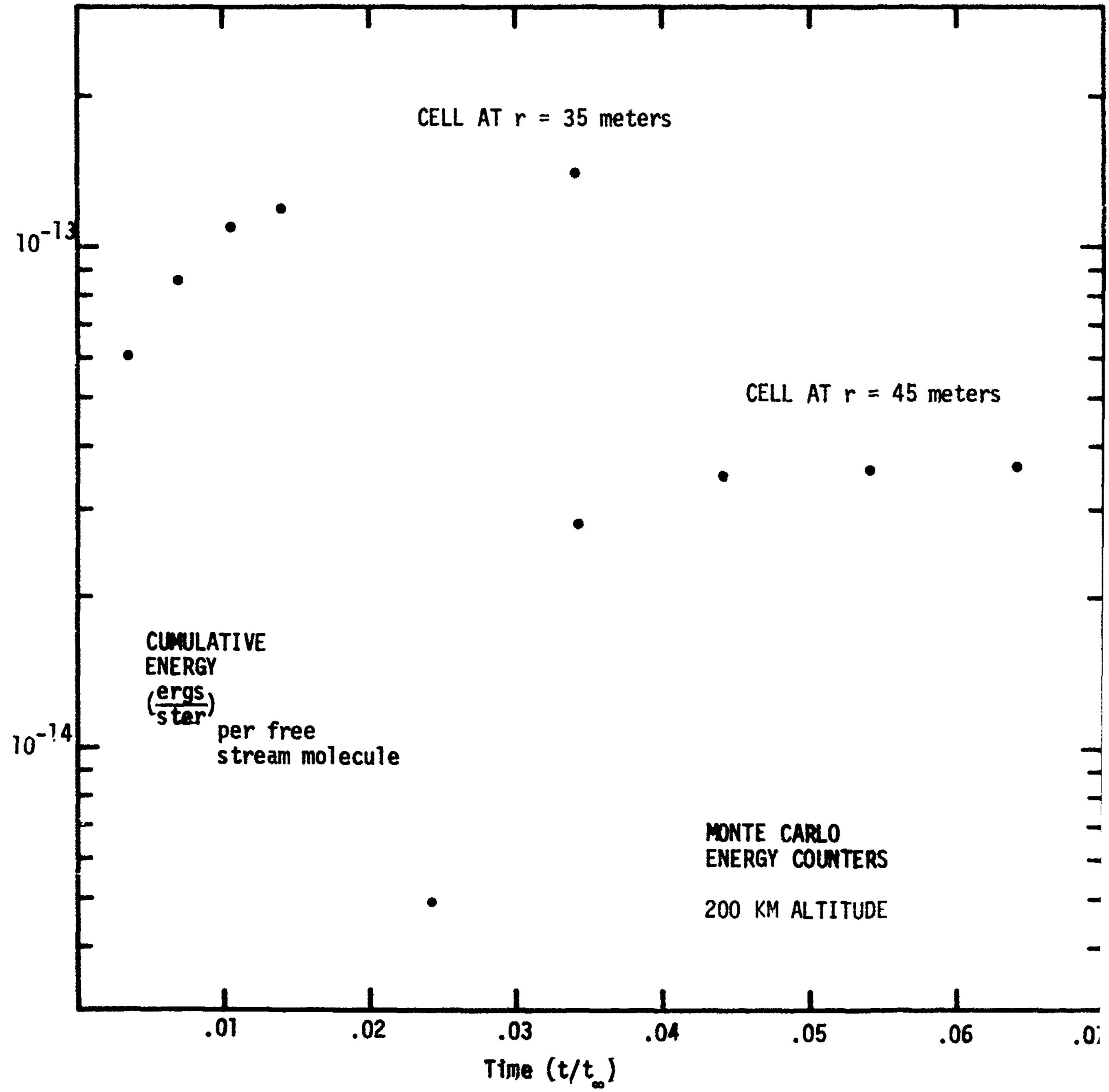

CELL AT r = 35 meters
10^{-13}
CELL AT r = 45 meters
CUMULATIVE
ENERGY
$(\frac{ergs}{ster})$ per free
stream molecule
10^{-14}
MONTE CARLO
ENERGY COUNTERS
200 KM ALTITUDE
.01
.02
.03
.04
.05
.06
Time (t/t_∞)

FIGURE 8

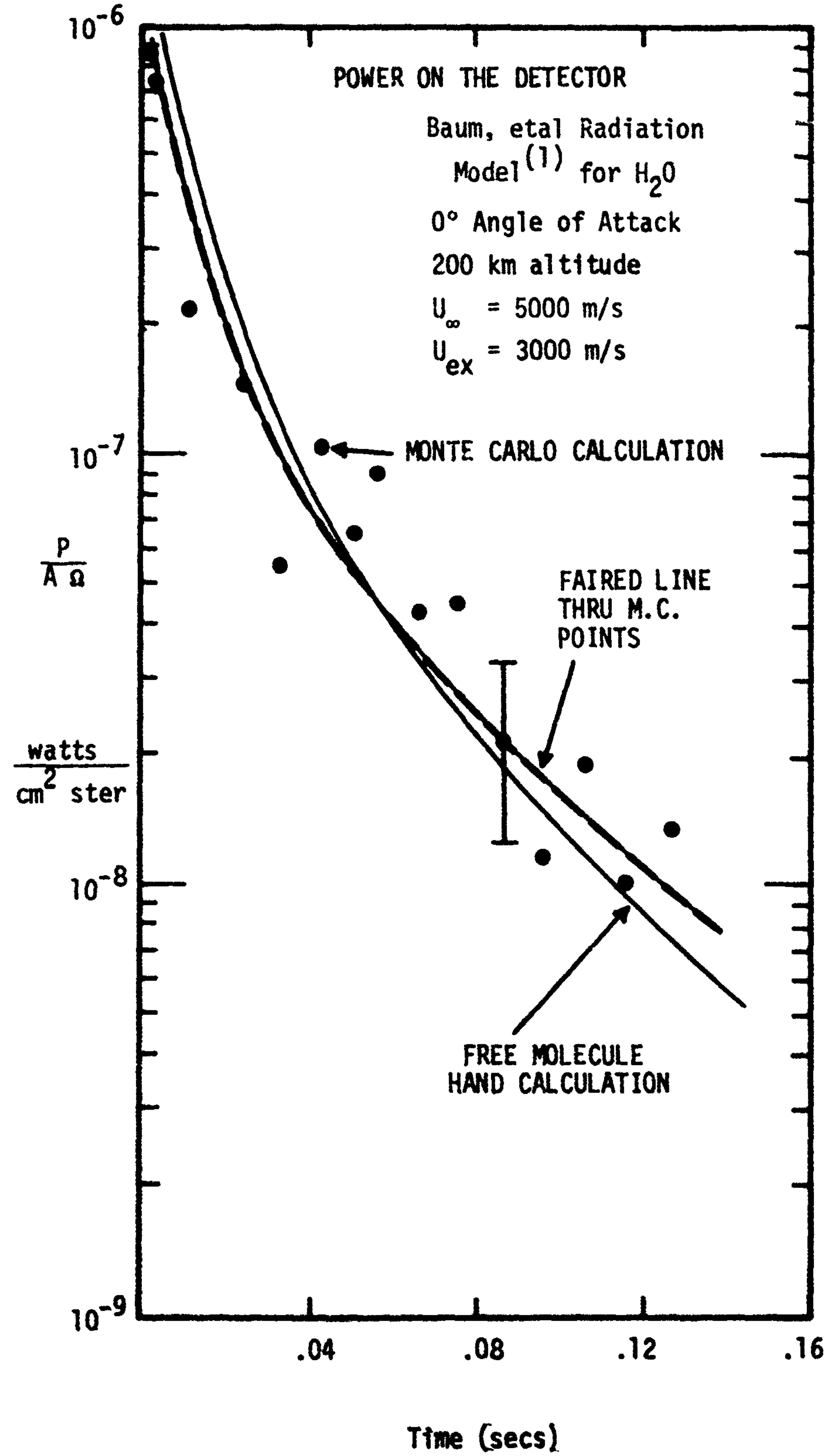

POWER ON THE DETECTOR
Baum, etal Radiation
Model(1) for H2O
0° Angle of Attack
200 km altitude
U∞ = 5000 m/s
Uex = 3000 m/s
MONTE CARLO CALCULATION
FAIRED LINE
THRU M.C.
POINTS
FREE MOLECULE
HAND CALCULATION
10-6
10-7
10-8
10-9
P/A Ω
watts/cm2 ster
.04
.08
.12
.16
Time (secs)

FIGURE 9

the exhaust molecule mean free time, and adjusting the power for other velocities by an integration over the free molecule relative velocity distribution using the analytic fit to the Baum, etal[1] curve in Figure 7, a generalized curve of power on the sensor which is valid within the "thin shell streaming regime" is shown in Figure 10.

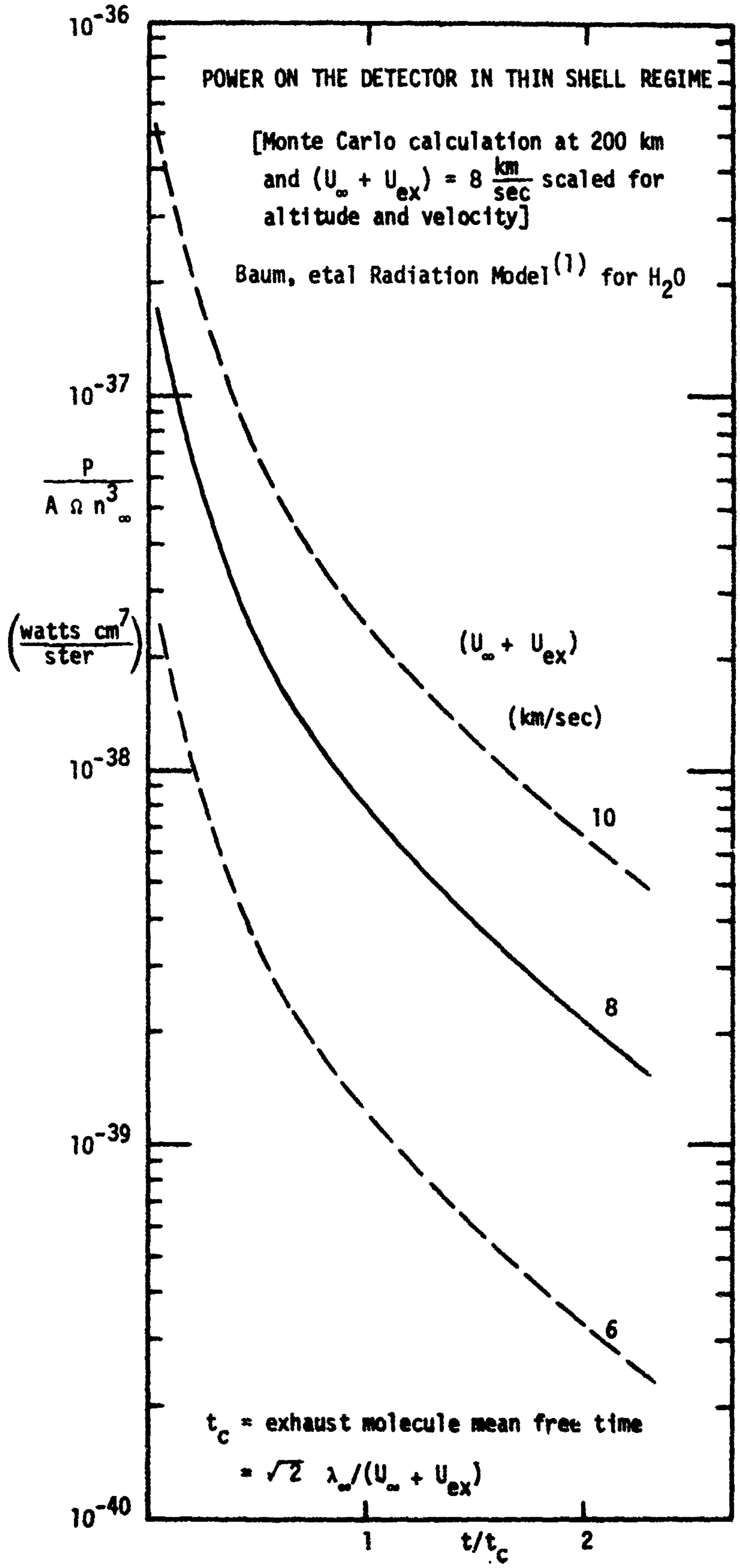

POWER ON THE DETECTOR IN THIN SHELL REGIME
[Monte Carlo calculation at 200 km and $(U_\infty + U_{ex}) = 8\ \frac{km}{sec}$ scaled for altitude and velocity]
Baum, etal Radiation Model[1] for H_2O
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
$\frac{P}{A\ \Omega\ n_\infty^3}$
$\left(\frac{\text{watts cm}^7}{\text{ster}}\right)$
$(U_\infty + U_{ex})$
(km/sec)
10
8
6
t_c = exhaust molecule mean free time
$= \sqrt{2}\ \lambda_\infty/(U_\infty + U_{ex})$
1
t/t_c
2

FIGURE 10

4. CONCLUSIONS

For rocket motor properties and operating characteristics of 600 pounds thrust and 7 milli-seconds burn time, it was found that:

1. At 200 km altitude, for time $\lesssim$ 3 mean free times ($\lesssim$ .2 secs), and for angles between relative wind and sensor look axis of 90° or less:

   a) the flow is in the "free streaming shell regime"

   b) the order of magnitude of the power on the detector can be estimated by a simple calculation -- the dominant contribution comes directly from a free molecular interaction between the shell of exhaust gas and the ambient gas

   c) the power on a detector can be scaled simply with magnitude and orientation of relative wind by taking the vector sum of U_∞ and $U_{exhaust}$ and then employing the effective radiation rate constant from Reference 1.

2. Conclusions in 1) above apply to higher altitudes with simple scaling.

3. The time for the disturbance to be blown away is sensitive to the orientation of the relative wind, but is greater than 3 mean free times for all orientations.